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Winter wheat water requirement and utilization efficiency under simulated climate change conditions: A Penman-Monteith model evaluation

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ABSTRACT

Impact of climate change on water supply and use is a critical issue for dryland crop production. In this study is assessed the potential impact of atmospheric CO_2 enrichment (500 μmol mol^{-1}, CE) and canopy warming (+2 °C, WA) and their combination (CW) on crop water utilization efficiency (*WUE*) of winter wheat in an open-air field experiment from Southeast China. Micro-meteorological measurement and wheat growth under individual treatments over three executive years of 2012–2015 were used to estimate the crop water requirement (*CWR*) of wheat using an improved FAO Penman-Monteith equation. Overall, CO_2 enrichment slightly decreased the *CWR* by 8.3%, and increased the *WUE* of grain production (*WUEg*) by 23.1%, averaged over the three years. In contrast, warming increased *CWR* by 19.6% but decreased *WUEg* by 27.9% over the period. Under CW treatment, however, *CWR* was increased by 3.1–15.8% but *WUEg* was decreased by 3.5–18.2% throughout three years. Clearly, the positive impact of CO_2 enrichment on *WUE* was largely negated under canopy warming. Moreover, when assessing with individual year data, inter-annual variability of *WUEg* was insignificant under WA, smaller under CE but much higher under CW, compared to CK. These results indicated that an interaction by canopy warming overshadowed the potential increase in *WUE* with CO_2 enrichment and enforced yearly fluctuation of the crop production under simulated climate change conditions. Therefore, improving water supply and management in agriculture should thus be endeavored to address the potential constraints with future trends of concurrent atmospheric CO_2 enrichment and warming.

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1. Introduction

World agriculture consumes about 70% of the world's freshwater and food security exerts a strong dependence on water resource availability (Bocchiola et al., 2013; Fader et al., 2011; Konar et al., 2011; Palazzoli et al., 2015). Water resource shortage has been increasingly constraining crop production (Piao et al., 2010; Wallace, 2000), challenged with the global climate change (Rosenzweig et al., 2014; Wheeler and von Braun, 2013). Increasing water utilization efficiency (*WUE*) would be a priority task among the key measures to sustaining global crop production in the coming decades (Elliott et al., 2014; Hoekstra and Mekonnen, 2012; Iglesias and Garrote, 2015; Ye et al., 2015). As one of most important non-irrigated staple crops (Ladha, 2003), winter wheat production has been constrained by decline in water availability with increasing drought frequency in recent years. Therefore, technologies to increase *WUE* would be measures to enhance climate-smart agriculture (Paustian et al., 2016).

Global atmospheric CO_2 concentration is expected to increase over 500 μmol mol^{-1}, while surface air temperature to elevate by about 2 °C during the middle of 21st century (IPCC, 2013; Solomon et al., 2009). This climate change would have great impacts on crop production (Guo et al., 2010; O'Leary et al., 2015), potentially through decreasing *WUE* by plants (Wallace, 2000). However, the impacts on crop water utilization could vary with climatic factors that influence the evapotranspiration and plant physiological processes. Elevated CO_2 concentration tends to decrease transpiration and seasonal crop water requirement (*CWR*) owing to decreased stomatal conductance (Shimono et al., 2013; Yu et al., 2007). Being often addressed as CO_2 fertilization effect, CO_2 enrichment could increase plant biomass and grain production, resulting in an apparent increase in *WUE* (Bunce, 2013; Hunsaker et al., 2000; O'Leary

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et al., 2015; Shimono et al., 2013; Yoshimoto et al., 2005). However, CO_2 enrichment could also negatively affect *CWR* for the potential increase in leaf area index (LAI) (Kim et al., 2003; Shimono et al., 2013) and photosynthetic rate (Ruiz-Vera et al., 2013). On the other hand, CO_2 enrichment could result in an increase in air temperature, which would generally increase *CWR* since evaporation and canopy transpiration could be increased (Goyal, 2004), and thus crop productivity decreased (Wang et al., 2016a) under elevated temperature. Meanwhile, elevated temperature could induce a shortened duration of crop growing (Cleland et al., 2007) and thus a decreased crop *CWR*. The net response of crop production to the combined effects of CO_2 enrichment and warming has been evaluated in previous studies (Kim et al., 1996; Ruiz-Vera et al., 2013; Usui et al., 2016), the majority of which suggested that the positive effect of CO_2 enrichment was often traded off by the negative effects of warming on crop production (Hasegawa et al., 2017; Wang et al., 2016a). Therefore, it is worthy to address the combined effects of CO_2 enrichment and warming on *CWR* and *WUE* under field conditions.

Modelling approaches had been employed in evaluating inter-annual variability of water consumption by crop in response to climate change conditions (Cammarano et al., 2016; O'Leary et al., 2015; Zhuo et al., 2014). Crop *WUE* was modeled to increase in a range of 7% to 120% between years under CO_2 enrichment in field and greenhouse studies (Hunsaker et al., 2000; Niu et al., 2011; Shimono et al., 2013; Tausz-Posch et al., 2013; Wu et al., 2004). In a modelling study by Cammarano et al. (2016), elevated temperature increased annual variability of *CWR*, regardless of CO_2 enrichment effects. However, large uncertainties existed among the modelling predictions of *CWR* or *WUE*, for the lack of field observations (Cammarano et al., 2016; Li et al., 2015). Therefore, to what extent the different climate change scenarios would impact the inter-annual variability of *CWR* and *WUE* is still unclear.

So far, over 50 mathematical estimations had been used for predicting evapotranspiration (ET) and *CWR*, with varying complexity using different variables (Lu et al., 2005; Islam et al., 2012). As recommended as a standard method of water requirement calculation by the International Commission on Irrigation and Drainage (ICID) and Food and Agricultural Organization of the United Nations (FAO), the use of the Penman-Monteith model directly incorporates the relevant meteorological variables and biophysical parameters (Allen et al., 1998). Later on, Penman-Monteith model had been concerned as the most reliable model worldwide (Kingston et al., 2009; Lu et al., 2005). Changes in atmospheric CO_2 concentration and temperature could modify the relevant physiological traits (e.g., leaf area, stomatal conductance) and also meteorological variables (e.g., temperature, rainfall, relative air humidity) of cropland, which are important for ET. Kingston et al. (2009) argued that Panman-Monteith was most reliable method among the six methods including Penman-Monteith, Hamon, Hargreaves, Priestley-Taylor, Blaney-Criddle, and Jensen-Haise models, when assessing potential ET. This model was constructed on a robust physical basis with all relevant meteorological variables and allowed to address non-meteorological uncertainties such as specification of canopy conductance.

The Penman-Menteith model had been also preferable for future climate change impact studies, for the model addresses changes rather in atmospheric variables than in edaphic conditions (Islam et al., 2012; Kingston et al., 2009). By modifying the canopy resistance term, Penman-Monteith model could effectively evaluate the impacts of global warming and CO_2 enrichment on ET (Islam et al., 2012; Priya et al., 2014; Wu et al., 2012). Therefore, Penman-Monteith model could directly be used to simulate ET and evaluate *CWR*. Moreover, the Penman-Monteith equation had been widely used to estimate crop evapotranspiration and water demand in simulated climate change experiments (Cammarano et al., 2016; Ewert et al., 2002; Goyal, 2004; Lovelli et al., 2010; Savabi and Stockle, 2001; Steduto et al., 2009).

China is one of the major crop production countries in the world (Frolking et al., 2002), of which the food safety is vulnerable global change and the associated extreme weather events (Lesk et al., 2016; Pan, 2010; Ray et al., 2015). Rice and wheat production from Asia could be greatly impacted by climate change conditions, possibly enhanced under CO_2 enrichment but negatively impacted by global warming (Hasegawa et al., 2017; Wang et al., 2016a). At particular, drought and water scarcity had become key constraints for crop production of China (Piao et al., 2010). To understand the effects of climate change on *CWR* and *WUE* is a prerequisite for developing such climate-smart agriculture of China.

So far, it remains unclear whether the effect of warming outweighed the effect of CO_2 enrichment in terms of *CWR* and *WUE*. This limits our ability to predict the potential impact of climate change on wheat productivity. We hypothesize that wheat *CWR* or *WUE* could vary with different sets of climate change conditions and exert inter-annual variability between years of the climate change simulation. Based on micro-meteorological data collected over three consecutive years from an open air field experiment in Southeast China, this study is to estimate the combined effects of CO_2 enrichment and warming on the status and stability of *CWR* and *WUE* using an improved Penman-Monteith equation. We aimed to provide critical information for water management improvement for wheat production facing climate change in the near future.

2. Materials and methods

2.1. Experiment site

Data for this study was from an open-air field experiment base simulating climate change conditions in a summer rice-winter wheat rotation system. Being initiated in 2010, the field experiment was located at Kangbo village (31°30′N, 120°33′E), Guli Township, Changshu Municipality in Jiangsu Province, China (Wang et al., 2016a). Being a typical rice/wheat producing area of China, the area is controlled by a subtropical monsoon climate. As illustrated in Fig. 1, total precipitation was 422.4 mm, 441.3 mm and 352.9 mm for the entire wheat growing season respectively of 2012–2013, 2013–2014 and 2014–2015 (Table 1). The soil is a cultivated Gleyic Stagnic Anthrosol formed on clayey lacustrine. The basic property of the topsoil at the start of the experiment was: soil pH (H_2O) 7.0, soil organic carbon 19.2 g kg^{-1}, total nitrogen 1.3 g kg^{-1}, total phosphorus 0.9 g kg^{-1}, total potassium 15.0 g kg^{-1}, and a bulk density of 1.2 g cm^{-3}. The soil texture is classified as loam with 33.8% sand, 38.6% silt and 27.6% clay.

2.2. Stimulated climate change condition

The climate change conditions simulated in the field experiment system were described in detail by Liu et al. (2015) and by Wang et al. (2016a). The treatments included ambient CO_2 concentration and temperature as control (CK), CO_2 enrichment up to 500 μmol mol^{-1} (CE), canopy air warming by 2 °C over ambient (WA), and concurrent CO_2 enrichment and canopy air warming (CW). CO_2 enrichment and crop canopy air warming were sustained throughout the whole crop growing period. The treatments were conducted in separated octagonal rings, each having an area of 50 m^2 in the field. Each treatment was replicated in three rings with the same infrastructure and the rings arranged in a split row design. All the rings were buffered by the adjacent open fields about 28 m apart to avoid any cross-over effects from the treatments.

For the atmospheric CO_2 enrichment treatments (CE and CW), pure CO_2 gas (purity 99.99%) were supplied using a liquid CO_2

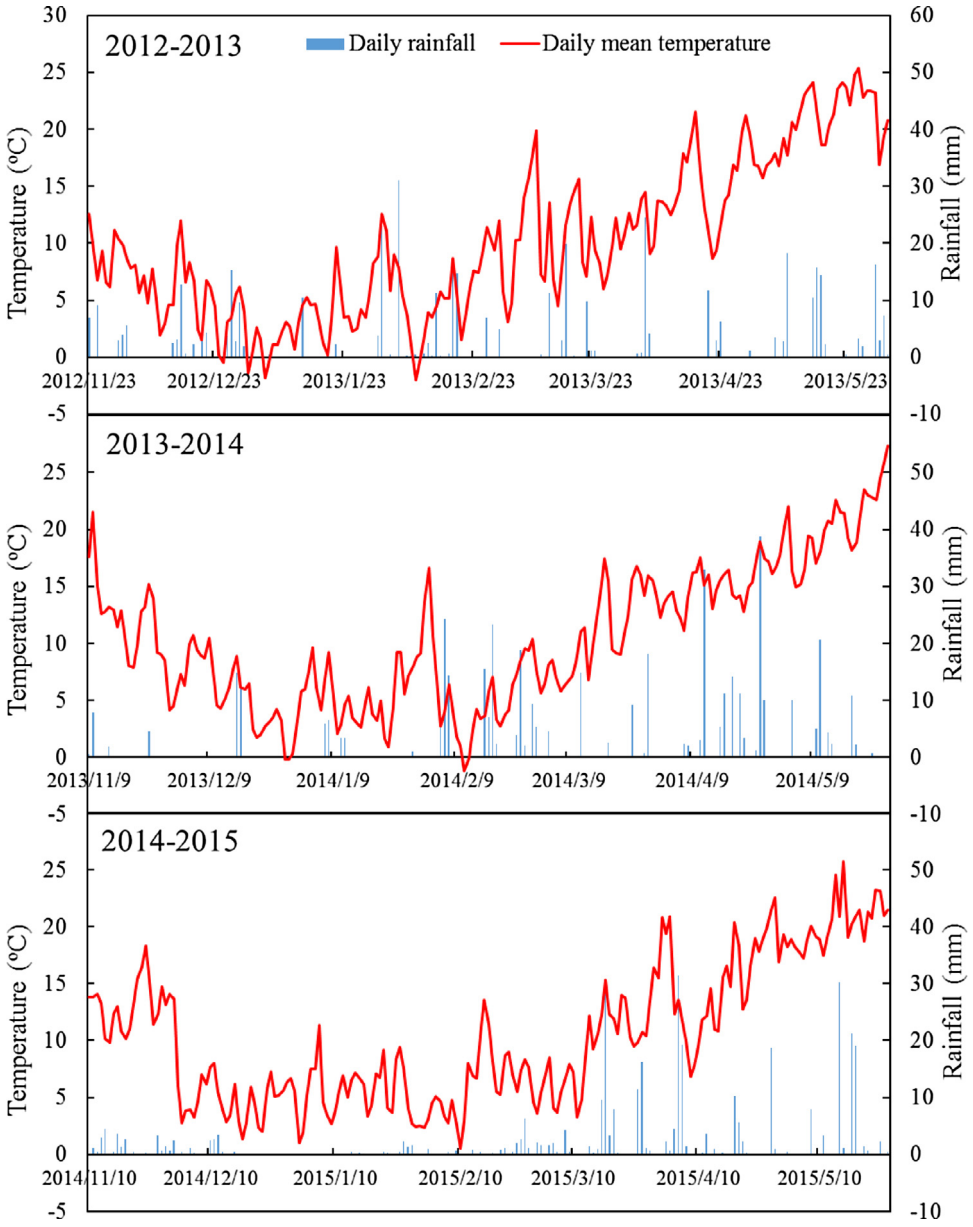

Fig 1. The daily rainfall and mean temperature during wheat growth over 2012–2015.

Table 1
Dates of wheat seeding and harvest, and summary of the weather conditions, and mean temperature increments and atmospheric CO_2 concentration under canopy warming or CO_2 enrichment treatment.

Rotation Year	Wheat seeding date	Harvest date	Daily mean minimum temperature (°C)	Daily mean maximum temperature (°C)	Daily mean temperature (°C)	Cumulative precipitation (mm)	Canopy warming (°C)	CO_2 enrichment ($\mu mol\ mol^{-1}$)
2012–2013	23/11/2012	02/06/2013	6.21	14.35	10.07	422.4	1.5 ± 0.7	505 ± 26
2013–2014	10/11/2013	29/05/2014	5.67	18.79	11.23	441.3	2.0 ± 0.3	511 ± 20
2014–2015	11/11/2014	17/05/2014	5.97	15.98	10.41	352.9	1.8 ± 0.8	509 ± 28

Notes: the canopy warming in treatments both of WA and CW; similarly, CO_2 enrichment in treatments both of CE and CW. CE, ambient temperature and CO_2 enrichment; WA, warming and ambient CO_2; CW, warming plus CO_2 enrichment.

tank that released CO_2 gas into the octagonal plot (ring hereafter) through perforated stainless steel pipes surrounding a ring. The rate of CO_2 gas release was manipulated automatically in accordance with the existing air CO_2 concentration, wind direction and speed. A total of 17 CO_2 gas monitoring points were evenly equipped over an octagonal ring, which was adjusted as the crop grew. The CO_2 pumping was automatically controlled with a Li-Cor CO_2 gas analyzer (LI-820; Li-Cor, Lincoln, NE, USA) by the ring.

For canopy warming treatments (WA and CW), a total of 12 infrared heaters (IR) (2000 W, 240 V, 1.65 m long × 0.14 m wide; HS-2420, Kalglo Electronics Co., Inc., Bethlehem, PA, USA) supplying 140 $W\ m^{-2}$ of IR, were mounted a ring, following the method proposed by Kimball (2005). The canopy temperature was moni-

tored by 5 infrared detector thermometers (Model SI-121, Apogee instruments Inc, Logan, USA) over crop canopy. The actual increment of canopy temperature and atmospheric CO_2 concentration during the three wheat cropping seasons are provided in Table 1.

2.3. Field management

As described in detail by Wang et al. (2016b), the field management was consistent across the treatment rings and rotation years. Briefly, winter wheat (*Triticum aestivum* L. cv) of a local cultivar Yangmai No.14 was planted at a density of 250 seedlings per m^2 with a row spacing of 20 cm. The wheat seeding and harvest dates are summarized also in Table 1. All the experimental plots were fertilized with urea (46% N) and compound fertilizer (15 N: 15 P_2O_5: 15 K_2O) for wheat growth. In detail, urea was applied at 187.5 kg ha^{-1} as basal fertilizers, and at 150 kg ha^{-1} as a topdressing at the jointing stage. Compound fertilizer was applied at 375 kg ha^{-1} as a topdressing after the heading stage. The basal fertilizer was broadcast and incorporated into the soil by ploughing to the depth of plow layer, and the topdressing was surface broadcast. Other farm managements including weed control, fertilization and insecticide application, were performed following the local conventional practices. The wheat crops were cultivated under rain-fed conditions in this study.

2.4. Sampling and measurement of wheat biomass and grain

Aboveground biomass (*AB*, t ha^{-1}) and grain yield (*GY*, t ha^{-1}) were determined to evaluate the impact of CO_2 enrichment and canopy warming on crop growth and production. At the ripening stage, all of the fresh aboveground biomass in each ring was collected and weighed individually in the field. To determine the dry weight for the aboveground biomass, three plant samples in a ring were randomly sampled and air-dried at 105 °C for 30 min and subsequently at 70 °C to constant weight. Meanwhile, all the grains from the collected biomass in a ring were threshed using a portable thresher. Grain moisture content was measured by drying a portion of grain, using similar method for dry biomass to allow estimation of grain production on dry weight base.

2.5. Meteorological monitoring and data archive

Daily weather conditions were monitored in a micro-weather station adjacent to the treatment field and the data was retrieved by a CR1000 Campbell data logger (Campbell Scientific Inc., Logan, UT, USA), which was equipped with a daily rainfall sensor (HMP155A, Campbell Scientific Inc., Logan, UT, USA) and a photosynthetically active radiation sensor (LI190SB; Li-Cor Inc., Lincoln, NE, USA). For a single treatment ring, the micro-meteorological data was recorded every minute including the mean air temperature, maximum air temperature, minimum air temperature through five infrared detector thermometers (Model SI-121, Apogee instruments Inc., Logan, USA), relative humidity through three air humidity sensors (Model HMP35C), wind speed at 2 m above ground by a wind anemometer (Model CSAT3), and actual vapor pressure throughout the whole day over the crop growing period. In order to ensure the accuracy of monitoring data, these sensors were regularly maintained during wheat growing.

For the different treatments, LAI (m^2 m^{-2}) is defined as the ratio of leaf area to land surface area, and is measured using the method developed by Yin et al. (2003). And crop growth data were reported by Cai et al. (2016).

2.6. Data treatment and calculations

2.6.1. Crop water requirement

Reference crop evapotranspiration rate (ET_o, mm day^{-1}) was calculated based on the Penman-Monteith equation recommended by FAO (Allen et al., 1998). Considering the stomatal conductance varying with atmospheric CO_2 concentration, the ET_o is calculated using the equation developed by Islam et al. (2012).

$$ETo = \frac{0.408\Delta(Rn - G) + r\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + r\left(1 + \frac{0.34U_2}{CO_2 factor}\right)} \quad (1)$$

Where, ET_o is the reference crop evapotranspiration rate (mm d^{-1}), and calculated with a daily time step in this study; *Rn* is the net radiation at the crop surface (MJ m^{-2} d^{-1}); *G* is the soil heat flux density (MJ m^{-2} d^{-1}); *T* is the daily mean temperature at crop canopy (°C); U_2 is the wind speed at a height of 2 m (m s^{-1}); e_s is the saturated water vapor pressure (kPa); e_a is the actual water vapor pressure (kPa); Δ is the slope of the saturation water vapor pressure-temperature curve (kPa °C^{-1}); γ is the psychometric constant (kPa °C^{-1}). The values for all these variables were treatment specific ones, measured at or calculated for each single treatment plot.

In the above equation, a *CO_2 factor* is used to adjust the changes with elevated CO_2 concentration (Islam et al., 2012; Priya et al., 2014; Wu et al., 2012). Based on eighty data sets comparing stomatal conductance under atmospheric CO_2 concentration from 330 μmol mol^{-1} to 660 μmol mol^{-1} for a wide range of species including wheat, Stockle et al. (1992) developed the linear relationship for leaf stomatal conductance as a function of CO_2 concentration. Morison and Gifford (1983) used a 40% linear decrease in stomatal conductance as CO_2 concentration varied from 330 μmol mol^{-1} to 660 μmol mol^{-1}. Thus, a CO_2 factor on stomatal conductance can be estimated with the following equation:

$$g_{CO_2} = g\left[(1 + p) - p\frac{CO_2}{330}\right] \quad (2)$$

Where, g_{CO2} represent modified stomatal conductance under elevated CO_2 (mol m^{-2} s^{-1}); *g* represent the reference stomatal conductance (mol m^{-2} s^{-1}) under a same wheat cultivar and biogeography condition with ambient CO_2 concentration (Feng et al., 2016); *p* is the percentage of decrement in stomatal conductance; CO_2 is atmospheric CO_2 concentration under CO_2 enrichment, and 330 represents the baseline atmospheric CO_2 concentration (μmol mol^{-1}).

The *CWR* (mm) is calculated as the total amount of water used for crop transpiration. Accordingly, the *CWR* could be calculated as the potential crop evapotranspiration adjusted with the crop coefficient (*Kc*):

$$CWR = \sum_{i=1}^{n} K_c ET_{0,i} \quad (3)$$

Where, *n* is number of days of the whole wheat growing period; $ET_{o,i}$ is the ET_o, (mm day^{-1}) of *i* th day; crop coefficient (K_C) including a basal crop (K_{CB}) and a soil evaporation coefficient (K_e):

$$K_C = K_{CB} + K_e \quad (4)$$

Where, K_{CB} adjusted with treatment specific data of the relative humidity and wind speed measured at each treatment plot. Following the recommendation by Allen et al. (1998), crop coefficient (K_{abadj}) could be calibrated using the following equation:

$$K_{cbadj} = K_{cb} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (5)$$

Where, K_{cb} is the crop coefficient defined by Allen et al. (1998) (K_{cini} = 0.5, K_{cmid} = 1.10, K_{cend} = 0.3) for wheat; U_2 is the wind speed at a height of 2 m (m s^{-1}); RH_{min} is the mean value of daily minimum relative humidity (%);h is the plant height during the mid or late growing stage (m).

In this study, crop leaf area could be affected by CO_2 enrichment and warming treatments. This could lead to changes in crop transportation and thus water utilization. Subsequently, the crop coefficient is considered in relation to treatment specific LAI using the experimental data:

$$K_{CB} = K_{abadj} - \left[1 - \left(\frac{LAI_t}{LAI_a}\right)^{0.5}\right] \quad (6)$$

Where, LAI_a and LAI_t is the leaf area index (m^2 m^{-2}) respectively under ambient condition and climate change treatments in this study (Cai et al., 2016).

In present study, soil evaporation coefficient (K_e) could be calibrated using the following equation by Allen et al. (1998):

$$K_e = \min\left\{K_r\left(K_{cmax} - K_{CB}\right), f_{ew}K_{cmax}\right\} \quad (7)$$

Where, min{} is the minimum value of the different products calculated with parameters included in the brakes {}; K_r is evaporation reduction coefficient; K_{cmax} is maximum value of K_c following rain; f_{ew} is fraction of the soil that is both exposed and wetted. K_{cmax} and f_{ew} could be expressed as:

$$K_e = \max\left(\left\{1.2 + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, (K_{CB} + 0.05)\right) \quad (8)$$

$$f_{ew} = min(1 - f_c, f_w) \quad (9)$$

$$f_c = \left(\frac{K_{CB} - K_{cmin}}{K_{cmax} - K_{cmin}}\right)^{(1+0.5h)} \quad (9a)$$

Where, $1 - f_c$ is the soil area not covered by crop [0.01-1]; f_w is the average fraction of soil area wetted by precipitation; K_{cmin} is the minimum K_c for dry bare soil with out ground cover.

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{for} D_{e,i-1} > \text{REW or } K_r = 1 \text{ for } D_{e,i-j} < \text{REW} \quad (10)$$

$$TEW = 1000\left(\theta_{fc} - 0.5\theta_{wp}\right)Z_e \quad (10a)$$

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) + \frac{E_i}{f_{ew}} + T_{eW,i} + DP_{e,i} \quad (10b)$$

Where, TEW (total evaporable water, mm) is the maximum depth of water; REW (readily evaporable water, mm) is cumulative depth of evaporation (depletion) at the end of stage, which is 10 mm as default in this study site; θ_{fc} and θ_{wp} (m^3 m^{-3}) represents soil water content at field capacity and at wilting point, being 0.29 m^3 m^{-3} and 0.16 m^3 m^{-3}, respectively; $D_{e,i}$ and $D_{e,i-1}$ (mm) is cumulative depth of evaporation (depletion) from the soil surface layer respectively at the day i and at the end of day i-1; P_i and RO_i (mm) is respectively precipitation and precipitation runoff from the soil surface on day i; $T_{eW,i}$ represents the depth of transpiration on day i; $DP_{e,i}$ (mm) is the deep percolation loss from the topsoil layer on day i.

2.6.2. Water utilization efficiency of biomass and grain yield

Water utilization efficiency of biomass (*WUEb*, g m^{-2} mm^{-1}) and of grain yield (*WUEg*, g m^{-2} mm^{-1}) is respectively the ratios of the *AB* and *GY* per unit area to amount of the *CWR* (mm) over the growing season using the equations:

$$WUEb = \frac{AB}{CWR} \quad (11)$$

$$WUEg = \frac{GY}{CWR} \quad (12)$$

2.6.3. Variability analysis

Given that the cultivars and farm management were consistent over the three-year experiment, the coefficient of variation (*C.V.*) could be used to evaluate the yearly variability in *CWR* and *WUE* in response to climate change. Therefore, the *C.V.* was calculated in this study as follows:

$$CV_{i,j} = \frac{\sum\left(C_{i,j,k} - MC_{i,j}\right)^2/3}{MC_{i,j}} \times 100 \quad (13)$$

Where, $CV_{i,j}$ represents the *C.V.* of a ring i under a treatment j; $C_{i,j,k}$ is the *CWR* or *WUE* of a ring i under a treatment j in k^{th} year; and $MC_{i,j}$ is the mean *CWR* or *WUE* of a ring i under a treatment j.

2.7. Statistical analysis

All data were expressed as means plus standard deviation of three replicates. One-way ANOVA followed by Duncan's test was used to justify the differences between different treatments. A general linear mixed model (*GLM*) was used to test the major effects of CO_2 enrichment, canopy warming and/or growth year and their interactions on wheat production, *CWR*, *WUE* and their variability. All statistical analyses were carried out using IBM SPSS ver. 20.0. A probability level of $p < 0.05$ was considered as statistically significant.

3. Results

3.1. Wheat productivity under simulated climate change

As shown in Table 2, the *AB* production of wheat on average was moderately increased (by 10.7%) under CO_2 enrichment, moderately decreased (by 17.0%) under warming treatment. The *GY* production followed a similar trend, with a smaller extent of change compared to *AB* production.

3.2. CWR *and* WUE *under simulated climate change*

The pattern of estimated daily *CWR* across the three wheat growing seasons is presented in Fig. 2. Clearly, daily *CWR* was remarkably variable with wheat growth stages, being higher in the middle to latter growth stages than at the early growth stage over the three years. Moreover, the dynamics of daily *CWR* with the growing stages was significantly affected by climatic change treatments. The rate of *CWR* under CE was significantly decreased. In contrast, the rate of *CWR* was significantly increased under warming treatments (WA and CW), though the extent of such change varied among growth stages. Overall, treatment of elevated temperature significantly increased the daily *CWR* at middle growth stage in 2014–2015, but over the entire growing season in 2012–2013 and 2013–2014.

As illustrated in Table 3, the *CWR* averaged over the three years was decreased by 8.3% under CO_2 enrichment ($p = 0.013$), but remarkably increased under canopy warming by a mean of 19.6% ($p < 0.001$). However, the results from CW showed that *CWR* were increased by 3.1–15.8% over the three consecutive years.

When averaged for the three years, the *WUEg* and *WUEb* were increased respectively under CO_2 enrichment by a mean of 23.1% and of 20.6% ($p < 0.001$). In contrast, the *WUEg* and *WUEb* under

Table 2
Changes in grain yield (*GY*, t ha^{-1}), aboveground biomass (*AB*, t ha^{-1}) under different treatments. Values are means of the three replicates for each treatment.

Year	Temperature	*GY* (t ha^{-1})		*AB* (t ha^{-1})	
		Ambient	CO_2 enrichment	Ambient	CO_2 enrichment
2012–2013	Ambient	3.21	4.16	6.31	7.66
	Warming	2.79	2.90	5.05	5.10
2013–2014	Ambient	3.48	3.90	6.17	6.79
	Warming	2.93	3.32	4.87	5.74
2014–2015	Ambient	5.68	5.95	11.9	13.61
	Warming	4.81	5.66	11.27	11.52
Effect of CO_2 (%)		13.6%		10.7%	
Effect of warming (%)		−15.6%		−17.0%	
CO_2		0.001		0.002	
Warming		<0.001		<0.001	
Year		<0.001		<0.001	
CO_2 × Warming		0.717		0.091	
CO_2 × Year		0.863		0.877	
Warming × Year		0.599		0.425	
CO_2 × Warming × Year		0.089		0.280	

Notes: CK, ambient temperature and ambient CO_2; CE, ambient temperature and CO_2 enrichment; WA, warming and ambient CO_2; CW, warming and CO_2 enrichment.

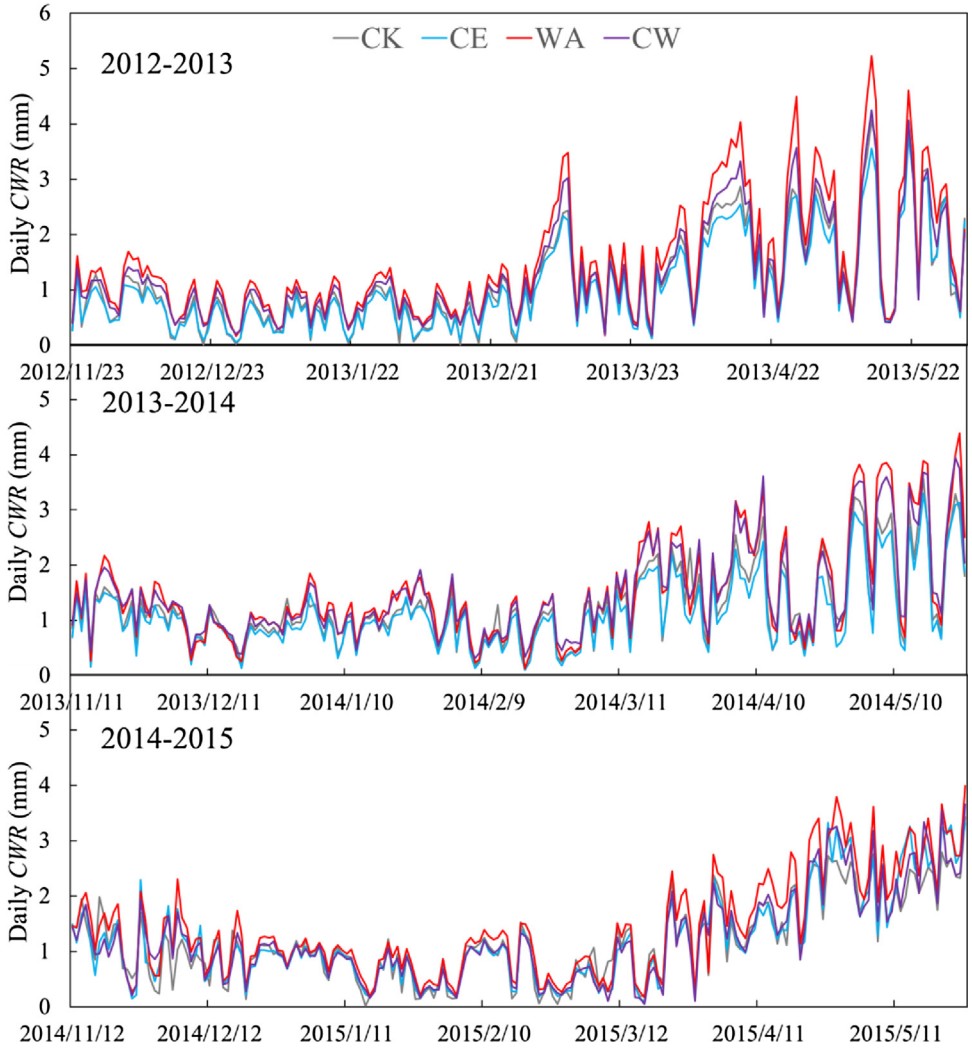

Fig. 2. Change in daily crop water requirement (*CWR*, mm) for wheat under different treatments during the three wheat growing seasons. Notes: CK, ambient temperature and ambient CO_2; CE, ambient temperature and CO_2 enrichment; WA, warming and ambient CO_2; CW, warming and CO_2 enrichment. Values are means of the three replicates for each treatment.

Table 3
Changes in crop water requirement (*CWR*, mm), and water utilization efficiency of grain yield (WUE_g, g m^{-2} mm^{-1}) and biomass (WUE_b, g m^{-2} mm^{-1}) under different treatments. Values are means of the three replicates for each treatment.

Year	Temperature	*CWR* (mm)		*WUEg* (g m^{-2} mm^{-1})		*WUEb* (g m^{-2} mm^{-1})	
		Ambient	CO_2 enrichment	Ambient	CO_2 enrichment	Ambient	CO_2 enrichment
2012–2013	Ambient	222.78	202.26	1.44	2.07	2.83	3.79
	Warming	286.25	245.54	0.98	1.18	1.77	2.08
2013–2014	Ambient	262.21	234.99	1.33	1.66	2.35	2.90
	Warming	309.61	303.54	0.95	1.10	1.57	1.90
2014–2015	Ambient	237.04	242.05	2.40	2.46	5.02	5.68
	Warming	287.30	244.30	1.67	2.32	3.92	4.72
Effect of CO_2 (%)		−8.3%		23.1%		20.6%	
Effect of warming (%)		19.6%		−27.9%		−29.3%	
CO_2		0.013		<0.001		<0.001	
Warming		<0.001		<0.001		<0.001	
Year		0.004		<0.001		<0.001	
CO_2 × Warming		0.342		0.926		0.290	
CO_2 × Year		0.753		0.356		0.565	
Warming × Year		0.247		0.105		0.188	
CO_2 × Warming × Year		0.237		0.001		0.369	

Notes: CK, ambient temperature and ambient CO_2; CE, ambient temperature and CO_2 enrichment; WA, warming and ambient CO_2; CW, warming and CO_2 enrichment.

canopy warming were both significantly ($p < 0.001$) decreased by over 25.0% ($p < 0.001$) during the three years.

3.3. *Inter-annual variability of* CWR *and* WUE *under simulated climate change*

The values of *CWR* and *WUE* are different among the three consecutive years ($p < 0.05$), with the highest *CWR* observed in the hot season of 2013–2014 and with the highest *WUEg* and *WUEb* found in the dry season of 2014–2015 (Table 3). Unlike the biomass production (Table 2), decreases over ambient in *WUEg* and *WUEb* were by a range of 3.5%-26.7% under CW throughout the three consecutive years. However, the *WUEg* was significantly increased by CO_2 enrichment under canopy warming condition in 2014–2015, indicating a significant interaction of CO_2 × Warming × Year on *WUEg* ($p = 0.001$). In addition, an increase over ambient in *WUEg* and *WUEb* was observed respectively in a range of 2.7–43.2% and 13.1–34.0% under CE throughout the three years.

As exhibited in Fig. 3, the *C.V.* values with years of *CWR*, *WUEb* and *WUEg* varied in a wide range of 4.8–53.8%, exhibiting a great but different inter-annual variability under different treatments. Generally, the *C.V.* of *CWR* largely consistent among the simulated climate change treatments. Compared to ambient condition, the *C.V.* values both of *WUEb* and *WUEg* were much higher under CW but much lower under CE, while the *C.V.* values of *WUEg* unchanged under WA.

4. Discussion

4.1. *Effect of CO_2 enrichment and canopy air warming on wheat* CWR *and* WUE

Over the three consecutive years, the daily *CWR* was lower in early growth stage and higher in late growth stage due to the increased daily mean temperature. In a study by Liu et al. (2016) using lysimetric experiment of winter wheat in a similar region of China, daily *CWR* was low prior to the reviving stage but high after the jointing stage. In this study, winter wheat *CWR* was averaged of 256.5 mm over the three years. This could be comparable to the finding of 290 mm by Liu et al. (2007) for the same crop from Shanghai, China.

Decreases in *CWR* and increases in *WUE* had been reported for rice and wheat under CO_2 enrichment in many field experiments (Houshmandfar et al., 2016; Shimono et al., 2013; Tausz-Posch et al., 2013; Yoshimoto et al., 2005). Firstly, CO_2 fertilization effect could result in increases in photosynthetic rate and carbohydrate accumulation (Ainsworth and Long, 2005; Hasegawa et al., 2013; O'Leary et al., 2015). Accordingly, we observed *AB* and *GY* of wheat being increased moderately (both over 10% on average) under CO_2 enrichment, regardless of temperature (Table 2). Secondly, plant leaves received enough CO_2 for photosynthesis and greater depolarization of guard cells, leading to a decline in stomatal aperture and in leaf transpiration rate and thus to a reduced *CWR* under CO_2 enrichment (Ainsworth and Rogers, 2007; Shimono et al., 2013; Yu et al., 2007). The present study revealed a significant positive effect of CO_2 enrichment on *WUEg* and *WUEb*, which was increased respectively by 23.1% and 20.6% on average over the three years under CO_2 enrichment, regardless of temperature (Table 3). This was comparable to finding by Qiao et al. (2010) in a greenhouse experiment, where CO_2 concentration was up to 712 μmol mol^{-1}. Of course, our finding here was much lower than a 57% increase in wheat *WUE* under atmospheric CO_2 concentrations up to 550 μmol mol^{-1} in a FACE field study from Australian (Tausz-Posch et al., 2013). Moreover, CO_2 enrichment alone here increased *WUEg* and *WUEb* by over 30% and by over 20% respectively in normal precipitation season of 2012–2013 and 2013–2014 (Table 3). O'Leary et al. (2015) observed an increase in *WUE* of biomass and yield respectively by 31% and by 36% in wheat under CO_2 enrichment from Australia. Whereas, our results showed CO_2 enrichment slightly decreased *CWR*, which was in contrast to the finding by O'Leary et al. (2015), who reported that *CWR* was unchanged by CO_2 enrichment for late time of sowing wheat only under rain-fed in a FACE experiment. This inconsistency could be explained by the different CO_2 concentrations, treatment methods and environmental conditions between studies. Meanwhile, it is worth noting that the high variability of *CWR* and *WUE* was observed, for the decrements of *CWR* varied from 3.1% to 15.8% and increments of *WUE* varied from 2.7% to 43.2% under CO_2 enrichment alone throughout the monitoring years in this study (Table 3). Previous studies also showed the increments of *WUE* varied from 7% to 120% under CO_2 enrichment conditions (Hunsaker et al., 2000; Niu et al., 2011; Tausz-Posch et al., 2013; Wu et al., 2004). Altogether, these studies highlighted the uncertainty over the effects of CO_2 enrichment on agricultural *CWR* and *WUE* (Cammarano et al., 2016; Huang et al., 2016; Ray et al., 2015; Wang et al., 2016a).

In contrast to the positive effects of CO_2 enrichment, negative effect of canopy air warming on *WUE* were observed throughout the monitoring years (Table 3). Warming caused declines in photosynthesis, promoted vapor pressure deficit, leaf transpiration, surface evaporation and evapotranspiration, decreasing wheat grain yield

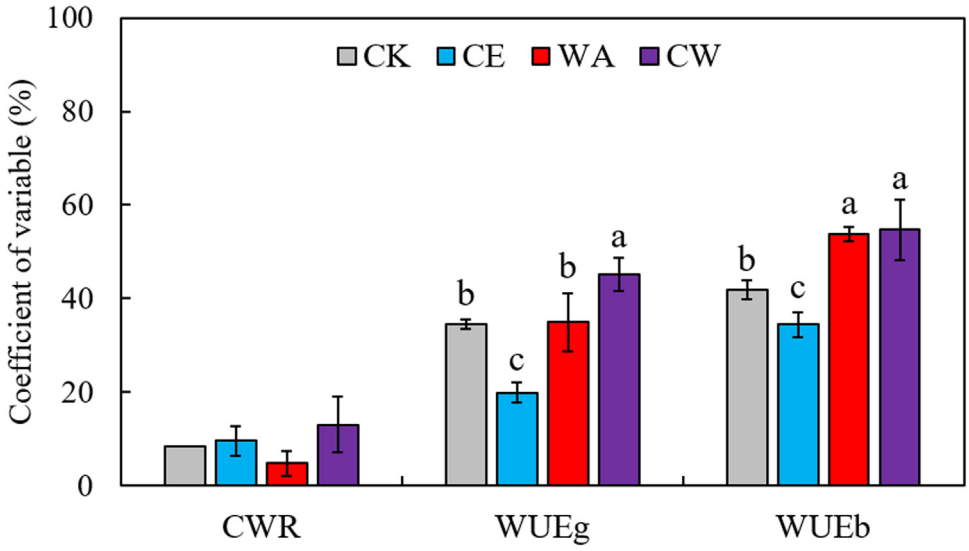

Fig. 3. Changes in coefficient of variation of crop water requirement (*CWR*), water utilization efficiency (*WUEg* and *WUEb*) under different treatments over three years. Notes: Different letters indicate significant differences between treatments at $P < 0.05$ by Duncan's test. CK, ambient temperature and ambient CO_2; CE, ambient temperature and CO_2 enrichment; WA, warming and ambient CO_2; CW, warming and CO_2 enrichment.

and *WUE* (Goyal, 2004; Ruiz-Vera et al., 2013; Wang et al., 2016a; Zelikova et al., 2015). In present study, the *CWR* was increased by about 20% under canopy warming, regardless of CO_2 enrichment (Table 3). This result was consistent with an increase of 15% for evapotranspiration under warming from arid regions of Rajasthan, India (Goyal, 2004). Here, a reduction by over 25% of wheat *WUEg* and *WUEb* was observed under WA treatment over the three years. Guo et al. (2010) reported a lower decrease (by 4.8-8.1%) in wheat *WUE* in a modeling study of wheat production with climate change condition in North China. Also, relatively lower decreases in *WUE* were noted in grassland and spring wheat under warming (Niu et al., 2011; Wall et al., 2011). Overall, *CWR* could be increased under warming with an extent varying with growth stages, weather-, plant- and region-specific conditions.

Our results here demonstrated that both *WUEb* and *WUEg* were decreased moderately under concurrent CO_2 enrichment and warming over the three years (Table 3). Unlike under CO_2 enrichment only, canopy warming imposed the effect of CO_2 enrichment on wheat *CWR*, because wheat *CWR* was slightly increased (by 3.1%–15.8%) when crop was treated concurrently with CO_2 enrichment and warming over the three years (Table 3). This suggests that a positive effect of CO_2 enrichment could be partially offset by the negative impact of warming on *WUEg* and *WUEb*. Guo et al. (2010) highlighted a potential increase in evapotranspiration and in turn a decrease in *WUE* with concurrent CO_2 enrichment and warming in a simulation study of wheat and maize rotation system form North China. Evenmore, Cammarano et al. (2016) reported that CO_2 enrichment (720 μmol mol^{-1}) did not offset crop *WUE* reduction caused by elevated temperature in wheat. These results indicated a stronger effect of canopy air warming on *WUE* of wheat than CO_2 enrichment under field conditions. Therefore, given the stronger responses detailed above, the overall negative effect of concurrent CO_2 enrichment and warming on winter wheat *WUE* should be considered in predicting the impacts of climatic change.

4.2. Inter-annual variability as influenced by climate change conditions

In this study with interaction of climate change conditions, inter-annual variability of *CWR* and *WUE* were both higher under CO_2 enrichment and warming conditions. Seemingly, the inter-annual climate variations could alter the responses of *WUE* to CO_2 enrichment and warming. Wisser et al. (2008) pointed out the variability and uncertainties of agricultural water requirement and global irrigation arising from inter-annual variability of weather and climate. In addition, canopy air warming decreased *WUEb* and *WUEg*, with the extent varying from 21.9% to 37.5% during the three years in this study (Table 3). This is comparable to the finding by Craufurd et al. (1999), who reported that the decrement of *WUE* under elevated temperature varied from 14.3% to 29.4% among years. These results evidenced a large uncertainty concerning the effect of climatic and atmospheric change on *CWR* and *WUE*.

To examine the causes of the inter-annual variability of *CWR* and *WUE*, we analyzed the cumulative precipitation across wheat growing seasons (Table 1). Plant water requirement could be affected by rainfall (Allen et al., 1998; Huang et al., 2016). In this study, *CWR* was affected by meteorological condition, being hottest in the season of 2013–2014 over the three years (Tables 1 and 3). However, the *WUEg* and *WUEb* were highest in the dry season of 2014–2015 over the monitoring years. This change in *WUE* could be ascribed to a decline in transpiration in lower temperature year and benefit winter wheat during dry season of 2014–2015. Piao et al. (2010) addressed the distribution of water resources as spatially and seasonally heterogeneous. Inter-annual variation of precipitation could be one of the major factors for the variability of *CWR* and *WUE* under CO_2 enrichment and warming.

Yet, canopy air warming significantly increased the inter-annual variability of *WUEb*, regardless of CO_2 enrichment (Fig. 3). Warming increased uncertainties of *CWR* and *WUE* of wheat under ambient and CO_2 enrichment conditions (Cammarano et al., 2016; Zhuo et al., 2014). The results here demonstrated that the *CWR* change was sensitive to daily mean temperature rather under warming condition than under CO_2 enrichment condition (Figs. 1 and 2). As simulated and predicted in previous studies, elevated temperature could increase the uncertainty of water utilization in wheat (Cammarano et al., 2016). Canopy warming by 2 °C resulted in higher inter-annual variability in the treatments of WA and CW in this study. Additionally, much higher inter-annual variability of *WUEg* and *WUEb* was observed under concurrent CO_2 enrichment and warming condition than under CO_2 enrichment alone, implying that warming significantly increased *C.V.* of *WUEg* under CO_2 enrichment condition (Fig. 3). Thus, an important interaction effect

between CO_2 enrichment and canopy air warming was observed in water utilization variability. Therefore, the future climate change research should simultaneously consider atmospheric CO_2 concentration and temperature. These findings suggest that increasing *WUE* under severe climate change is a great challenge faced by agriculture.

Out of our expectation, CO_2 enrichment alone tended to reduce the inter-annual variability of *CWR* and *WUE* (Fig. 3), which is important information for adaptation to climate change. Over the three years of study of *CWR* and *WUE*, we found a reduction of *CWR* and *C.V.* of *WUE* under CO_2 enrichment. However, winter wheat water consumption and uncertainty of *CWR* and *WUE* may increase in future climate change (concurrent CO_2 enrichment and warming) as per the above discussion, which will limit food production and supply. To adapt and mitigate the climate change effects on crop production in developing countries, technology to enhance *WUE* needs to develop in future study. One could breed wheat races to adapt to global warming and profit from CO_2 enrichment under climate change challenges (Ortiz et al., 2008). It is an important task for breeding to develop a new wheat cultivar, taking advantage of the positive aspects of CO_2 enrichment with restraining the negative effects of global warming on crop production and *WUE*.

5. Conclusion

In the present study, CO_2 enrichment decreased *CWR*, and increased *WUE*. In contrast, canopy warming significantly decreased *WUE* but increased *CWR*. The results from concurrent CO_2 enrichment and warming treatment indicated that the positive effect of CO_2 enrichment was unable to compensate for the negative effect of warming on *CWR* and *WUE*. A larger inter-annual variation of these responses was observed in concurrent CO_2 enrichment and warming condition, whereas the coefficient of variation was decreased under CO_2 enrichment alone, or unchanged under warming alone. Therefore, the on-going CO_2 enrichment and global warming could pose a critical challenge for sustaining food production globally. Moreover, future agricultural *CWR* and *WUE* under CO_2 enrichment and warming will face enormous challenges. We need to develop technology for agricultural water management, and take advantage of the positive aspects of CO_2 enrichment for adaptation to global warming in future climate change scenarios.

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